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Low cost measurement setup based on a piezoelectric microphone for estimating apple bruising using Shannon entropy

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ABSTRACT

This study presents a low cost measurement setup for estimating apple bruise volume during drop impact tests. The proposed measurement system consists of three main stages namely recording impact sound, signal processing, and estimating bruise volume. In the recording stage, the impact sound occurred when striking the apple on the surface was recorded by a piezoelectric microphone into computer. The impact sound was converted into Shannon entropy signals based on the Kernel density approach, and two measurable quantities namely entropy peak and pulse-width time were extracted from Shannon entropy signals in the signal processing stage. In the bruise volume estimating stage, the regression curves that map entropy peak and pulse-width features into bruise volume are estimated using measurements data. To evaluate the performance of the proposed method, we conducted several drop experiments with six different drop heights and two different temperatures (1 and 19 °C). Experimental results showed that bruise volume was exponentially proportional to the entropy peak and it was inversely proportional to pulse-width time as power functions, and all the curves were fitted with coefficients of determination of more than 0.98. Moreover, it was found that colder apples developed less bruise volume then warmer ones.

1. Introduction

Fruit bruising is one of the most important factors affecting fruit quality in the period from the tree to the market. In order to estimate fruit bruising, several methods have been developed, such as the drop impact test (McGlone et al., 1997; Ferreira, 2009; Celik et al., 2011; Jiménez-Jiménez et al., 2013; Boydas et al., 2014), pendulum test (Yurtlu and Erdoğan, 2005; Lewis et al., 2007; Ferreira, 2009; Ahmadi et al., 2010; Polat et al., 2012; Zarifneshat et al., 2012; Stropek and Gołacki, 2013), vibration test (Vursavuş and Özgüven, 2004), and compression test (Lewis et al., 2008; Ferreira, 2009; Kitthawee et al., 2011; Polat et al., 2012). The studies made in the area of impact bruising of apples which may occur during handling and transport have been classified and reviewed by Van Zeebroeck et al. (2007). Recently, Opara and Pankaj (2014) reviewed the studies related to destructive and non-destructive bruise measurement methods for fruit. Zhang and Brusewitz (1991) reported that the impact test represents the realistic load rather than the compression and vibration tests if the parameters can be sufficiently controlled. In the drop impact test, a few methods have been used to estimate bruise volume, such as video camera (Jiménez-Jiménez et al., 2013; Celik et al., 2011; Lewis et al., 2007), force transducer (McGlone et al., 1997; Ahmadi et al., 2010; Zarifneshat et al., 2012) and laser sensor systems (Boydas et al., 2014). Recently, Boydas et al. (2014) developed a relatively inexpensive measurement system based on a laser sensor to estimate apple bruising.

The objective of this study was to introduce a new low-cost measurement setup to estimate the bruise volume of apple during impact drop tests, exploring the novel relation between entropy and bruising concepts. For this purpose, we introduced a system based on a piezoelectric microphone (contact microphone) to measure bruise volume of apples dropped from certain heights on to steel plate. In a drop test, an apple is dropped from a certain height and it strikes onto the surface of a steel plate. A sound wave produced through the steel plate due to impact of the apple is measured by a piezoelectric microphone and is recorded on a computer as an impact sound signal. In the signal processing step, the envelope of the impact sound signal is extracted as follows. The impact sound signal is first divided into frames (small segments of sound signal)

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and for each frame the probability density function (pdf) is estimated based on a kernel density approach, and then the Shannon entropy signal which measures uncertainty (variance), is estimated using the related pdf of the frame. Using Shannon entropy signals, two efficiently measurable quantities, namely entropy peak and pulse-width time, are extracted for the purpose of estimation of bruising volume. Experimental results show that the apple bruise volume during a drop impact test can be estimated by using these quantities, accurately and reliably.

The main advantages of the proposed bruise volume estimation system are that it has a very much lower cost than other proposed systems given in the literature. There are three main reasons for a reduced cost of the proposed system. First, it uses a piezoelectric microphone to measure the impact activity, which has very much lower cost than other sensors, such as a force transducer (McGlone et al., 1997; Ahmadi et al., 2010; Zarifneshat et al., 2012), laser (Boydas et al., 2014) or high speed video (Lewis et al., 2007). Second, the proposed measurement system uses a sound card of the computer via a microphone input instead of an external data acquisition module to transfer the related data into the computer. Third, the proposed method uses free sound recording software instead of special expensive software to record the related impact activity. Therefore, the total cost of the proposed system is considerably lower than the systems given in the literature.

2. Materials and methods

A list of symbols and abbreviations used in this study is given in Table 1.

2.1. Research material

Apples (*Malus domestica* Borkh L. cv. Starking Delicious) were obtained from the cold storage of a supermarket. The mass of the apples was selected having almost uniform values ranging from 144 to 170 g to eliminate the effect of the mass on the bruise size.

2.2. Test apparatus

The drop impact test apparatus consisted of four parts as shown in Fig. 1: (1) a height gauge including a metal rod and a sliding height adjuster to control drop height, (2) a flat steel impact plate with thickness of 3 mm and a rubber plate placed under the steel plate to eliminate the undesired noise, (3) a piezoelectric microphone stuck on the top surface of the steel plate to measure impact sound, (4) a computer with sound recorder software. The piezoelectric microphone was connected to the computer through the microphone input using a wire to transmit the impact sound signals to the sound recorder.

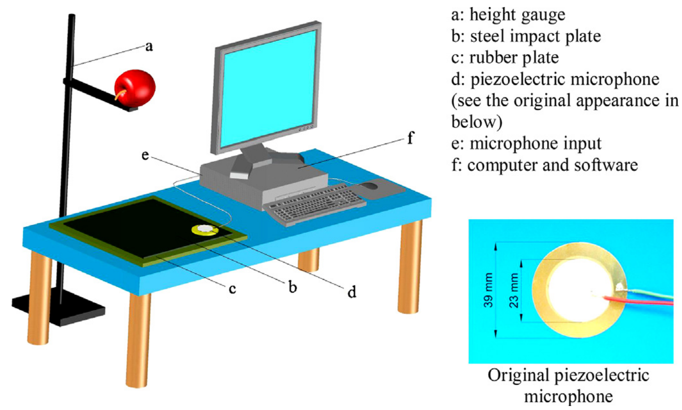

Fig. 1. Experimental apparatus.

2.3. Test procedure

The apples were divided into two groups; the first group was conditioned at 1 °C in a refrigerator, and the other one at 19 °C in the measurement room for 1 day prior to the drop impact tests. After the desired drop height was adjusted on the height gauge, each fruit was carefully released by hand without initial velocity to strike on the steel impact plate on its cheek. The fruit was caught by hand in the air just after the first impact to prevent the second one. The impact sound produced by the impact of the apple was sensed by the piezoelectric microphone and transmitted to the computer with the aid of a sound card and then stored for further analyses to estimate the apple bruising. In this study, the apples were dropped from six different heights of 20, 40, 60, 80, 100 and 120 cm. Tests were conducted 10 times for each drop height. A total of 120 fruit were used to estimate bruise volume after impact. All experiments were performed at the Biological Material Laboratory in the Agricultural Machinery Department of Atatürk University, Erzurum, Turkey.

2.4. Impact sound signal measurement via piezoelectric microphone

In the study, we used ordinary a piezoelectric microphone, with diameter of brass disk: 39 mm, diameter of center disk: 23 mm, frame depth: 0.25 mm, which was stuck on the surface of the steel impact plate as shown in Fig. 1. Its location can be selected anywhere on the surface of impact plate, but the apple dropped from a certain height should not strike it. The piezoelectric microphone was also connected to the computer (DELL OPTIPLEX 990) through a sound card at 44.1 kHz sampling frequency. When the apple impacted onto the surface of steel plate, mechanical waves (sound waves) travel through steel plate, and they bend the piezoelectric material, which produces an electrical potential. This electrical potential is amplified by the computer sound card and recorded

Table 1
List of symbols and abbreviations.

D	Bruise diameter (cm)	N	Number of observation samples
W	Bruise width (cm)	p	Entropy peak (nats)
P	Bruise depth (cm)	t_w	Pulse-width time (s)
h	Drop height (cm)	R^2	Coefficient of determination
V	True bruise volume (cm^3)	X	Random variable
$\hat{V}$	Estimated bruise volume (cm^3)	M	Mean value
e	Base of natural logarithm	σ^2	Variance
H	Shannon entropy	$\hat{\sigma}$	Estimated standard deviation
$\hat{H}$	Estimated Shannon entropy	$\psi_h(\cdot)$	Kernel function
h_b	Bandwidth	$f(\cdot)$, $g(\cdot)$,	Regression functions
$p(x)$	Probability density function	$s(\cdot)$, $z(\cdot)$	